

Pentaquarks and resonances in the pJ/ψ spectrum

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Abstract

We consider exotic baryons with hidden charm as antiquark-diquark-diquark composite systems. Spin and isospin structure of such exotic states is given and masses are estimated. The data for production of pentaquarks in the reaction $\Lambda_b \rightarrow K^- pJ/\psi$ are discussed. We suggest that the narrow peak in pJ/ψ spectra at 4450 MeV is antiquark-diquark-diquark state with negative parity, $5/2^-$ (4450), while the broad bump $3/2^+$ (4380) is the result of rescatterings in the (pJ/ψ) -channel. Positions of other pentaquarks with negative parity are estimated.

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1 Introduction

Data for the decay $\Lambda_b^0 \rightarrow pJ/\psi K^-$ [1] provide a definite argument for the existence of a pentaquark, a baryon system in pJ/ψ spectra which has the following quark content:

$$P_{\bar{c}cuud}^+ = \bar{c}(cuud). \quad (1)$$

In terms of the quark-diquark states it can be presented as a three-body systems:

$$\bar{c}(cuud) = \bar{c} \cdot (cu) \cdot (ud) + \text{permutations of the } u, d \text{ quarks}. \quad (2)$$

A diquark is a color triplet member, similar to a quark, and the right-hand side of eq. (2) presents a three-body system with a color structure similar to that in low-lying baryons. It is reasonable to suppose that we face similar color forces in three quark and antiquark-diquark-diquark systems as well. Following this idea we perform a classification of such baryon states and give estimations of their masses. Estimation of diquark masses is given in [2] where diquark-antidiquark states are studied.

The notion of the diquark was introduced by Gell-Mann [3]. Diquarks were discussed for baryon states during a long time, see pioneering papers [4, 5, 6, 7, 8] and conference presentations [9, 10, 11]. The systematization of baryons in terms of the quark-diquark states is presented in [12, 13]. The application of the diquarks to exotic mesons in the sector of heavy diquarks was discussed by Maiani *et al.* [14], Voloshin [15], Ali *et al.* [16].

Pentaquarks built of light-light and light-heavy diquarks present natural extension of multi-quark schemes studied in the last decade for mesons [17, 18] and baryons [19, 20].

2 Pentaquarks

In color space we write for the pentaquark:

$$P_{\bar{c}cuud}^+ = \epsilon_{\alpha\beta\gamma} \bar{c}^\alpha (cu)^\beta (ud)^\gamma + \text{permutations of the } u, d \text{ quarks} \quad , \quad (3)$$

$$(cu)^\beta = \epsilon^{\beta\beta'\gamma'} c_{\beta'} u_{\gamma'}, \quad (ud)^\gamma = \epsilon^{\gamma\beta''\gamma''} u_{\beta''} d_{\gamma''},$$

where α, β, γ refer to color indices.

We discuss a scheme in which the exotic baryon states are formed by standard QCD-motivated interactions (gluonic exchanges, confinement forces) but in addition with diquarks as constituents.

2.1 Spin structure of the pentaquarks

We work with two diquarks: scalar S and axial-vector A . In terms of these diquarks the color-flavor wave function of pentaquark reads:

$$P_{\bar{c}(cq)\cdot(q'q'')} = \bar{c}^\alpha \cdot \epsilon_{\alpha\beta\gamma} \begin{vmatrix} S_{(cq)}^\beta \\ A_{(cq)}^\beta \end{vmatrix} \cdot \begin{vmatrix} S_{(q'q'')}^\gamma \\ A_{(q'q'')}^\gamma \end{vmatrix} \quad (4)$$

We have six diquark-diquark states:

$$P_{\bar{c}(cq)\cdot(q'q'')} = \bar{c}^\alpha \cdot \begin{vmatrix} (S_{(cq)} S_{(q'q'')})^\alpha(0^+) \\ (S_{(cq)} A_{(q'q'')})^\alpha(1^+) \\ (A_{(cq)} S_{(q'q'')})^\alpha(1^+) \\ (A_{(cq)} A_{(q'q'')})^\alpha(0^+) \\ (A_{(cq)} A_{(q'q'')})^\alpha(1^+) \\ (A_{(cq)} A_{(q'q'')})^\alpha(2^+) \end{vmatrix} \quad (5)$$

with the spin-parity numbers $J^P = 0^+, 1^+, 2^+$.

2.2 Isospin structure of the diquarks

We face the following isospin states for the diquarks:

$$\begin{aligned} S_{(cq)}(I_d = 1/2, J_d = 0), & \quad A_{(cq)}(I_d = 1/2, J_d = 1), \\ S_{(q'q'')}(I_d = 0, J_d = 0), & \quad A_{(q'q'')}(I_d = 1, J_d = 1). \end{aligned} \quad (6)$$

So, the isospin-spin sector of the pentaquarks $P(I, J^P)$ reads:

$$P_{\bar{c}(cq) \cdot (q'q'')} = \bar{c}^\alpha \cdot \begin{vmatrix} (S_{(cq)} S_{(q'q'')})^\alpha (0^+) \\ (S_{(cq)} A_{(q'q'')})^\alpha (1^+) \\ (A_{(cq)} S_{(q'q'')})^\alpha (1^+) \\ (A_{(cq)} A_{(q'q'')})^\alpha (0^+) \\ (A_{(cq)} A_{(q'q'')})^\alpha (1^+) \\ (A_{(cq)} A_{(q'q'')})^\alpha (2^+) \end{vmatrix} \Rightarrow \begin{matrix} P(\frac{1}{2}, \frac{1}{2}^-) \\ P(\frac{1}{2}, \frac{1}{2}^-), P(\frac{1}{2}, \frac{3}{2}^-), P(\frac{3}{2}, \frac{1}{2}^-), P(\frac{3}{2}, \frac{3}{2}^-), \\ P(\frac{1}{2}, \frac{1}{2}^-), P(\frac{1}{2}, \frac{3}{2}^-) \\ P(\frac{1}{2}, \frac{1}{2}^-), P(\frac{3}{2}, \frac{1}{2}^-) \\ P(\frac{1}{2}, \frac{1}{2}^-), P(\frac{1}{2}, \frac{3}{2}^-), P(\frac{3}{2}, \frac{1}{2}^-), P(\frac{3}{2}, \frac{3}{2}^-) \\ P(\frac{1}{2}, \frac{3}{2}^-), P(\frac{1}{2}, \frac{5}{2}^-), P(\frac{3}{2}, \frac{3}{2}^-), P(\frac{3}{2}, \frac{5}{2}^-) \end{matrix} \quad (7)$$

2.3 Pentaquarks, their masses and spins

Mass formula for a diquark-diquark system $(cq) \cdot (q'q'')$, is accepted to be the same as for the diquark-antidiquark one [2]. We write

$$M_{(cq) \cdot (q'q'')} = m_{(cq)} + m_{(q'q'')} + J_{(cq) \cdot (q'q'')} (J_{(cq) \cdot (q'q'')} + 1) \Delta \quad (8)$$

with the parameters which were determined in ref. [2]:

$$\Delta = 70 \pm 10 \text{ MeV}, \quad (9)$$

$$m_{S_{(cq)}} = 2000 \pm 50 \text{ MeV}, \quad m_{A_{(cq)}} = 2050 \pm 50 \text{ MeV}.$$

Here we concentrate our attention on non-strange diquarks only, for an expansion of the results to the strange quark sector we need $m_{S_{(cs)}}$ and $m_{A_{(cs)}}$.

For the $(q'q'')$ diquarks we accept masses found in the analysis of baryons [12, 13]:

$$m_{S_{(q'q'')}} = 650 \pm 50 \text{ MeV}, \quad m_{A_{(q'q'')}} = 750 \pm 50 \text{ MeV}. \quad (10)$$

The mass of the constituent antiquark \bar{c} is equal to [21, 22]:

$$m_c = 1300 \pm 50 \text{ MeV}. \quad (11)$$

Within these masses (9),(10),(11) we roughly estimate the masses of the pentaquarks as:

$$M_{\bar{c}(cq) \cdot (q'q'')} \simeq m_{\bar{c}} + M_{(cq) \cdot (q'q'')} . \quad (12)$$

Correspondingly we write a set of the low-laying pentaquark states:

$I = 1/2$	$I = 3/2$
$P_{\bar{c} S_{(cq)} S_{(q'q'')}}^{(\frac{1}{2}, \frac{1}{2}^-)} (3800),$	$P_{\bar{c} S_{(cq)} A_{(q'q'')}}^{(\frac{3}{2}, \frac{1}{2}^-)} (4190), P_{\bar{c} S_{(cq)} A_{(q'q'')}}^{(\frac{3}{2}, \frac{3}{2}^-)} (4190),$
$P_{\bar{c} S_{(cq)} A_{(q'q'')}}^{(\frac{1}{2}, \frac{1}{2}^-)} (4190), P_{\bar{c} S_{(cq)} A_{(q'q'')}}^{(\frac{1}{2}, \frac{3}{2}^-)} (4190),$	$P_{\bar{c} A_{(cq)} S_{(q'q'')}}^{(\frac{1}{2}, \frac{1}{2}^-)} (4140), P_{\bar{c} A_{(cq)} S_{(q'q'')}}^{(\frac{1}{2}, \frac{3}{2}^-)} (4140),$
$P_{\bar{c} A_{(cq)} S_{(q'q'')}}^{(\frac{1}{2}, \frac{1}{2}^-)} (4140), P_{\bar{c} A_{(cq)} S_{(q'q'')}}^{(\frac{1}{2}, \frac{3}{2}^-)} (4140),$	$P_{\bar{c} A_{(cq)} A_{(q'q'')}}^{(\frac{1}{2}, \frac{1}{2}^-)} (4100),$
$P_{\bar{c} A_{(cq)} A_{(q'q'')}}^{(\frac{1}{2}, \frac{1}{2}^-)} (4100),$	$P_{\bar{c} A_{(cq)} A_{(q'q'')}}^{(\frac{3}{2}, \frac{1}{2}^-)} (4100),$
$P_{\bar{c} A_{(cq)} A_{(q'q'')}}^{(\frac{1}{2}, \frac{3}{2}^-)} (4240), P_{\bar{c} A_{(cq)} A_{(q'q'')}}^{(\frac{1}{2}, \frac{5}{2}^-)} (4240),$	$P_{\bar{c} A_{(cq)} A_{(q'q'')}}^{(\frac{3}{2}, \frac{3}{2}^-)} (4240), P_{\bar{c} A_{(cq)} A_{(q'q'')}}^{(\frac{3}{2}, \frac{5}{2}^-)} (4240),$
$P_{\bar{c} A_{(cq)} A_{(q'q'')}}^{(\frac{1}{2}, \frac{5}{2}^-)} (4520), P_{\bar{c} A_{(cq)} A_{(q'q'')}}^{(\frac{1}{2}, \frac{7}{2}^-)} (4520),$	$P_{\bar{c} A_{(cq)} A_{(q'q'')}}^{(\frac{3}{2}, \frac{5}{2}^-)} (4520), P_{\bar{c} A_{(cq)} A_{(q'q'')}}^{(\frac{3}{2}, \frac{7}{2}^-)} (4520).$

(13)

Masses are given in MeV units, an uncertainty in the determination of masses is of the order of ± 150 MeV.

3 Discussion

The state $P_{\bar{c}A_{(cq)}A_{(q'q'')}}^{(\frac{1}{2}, \frac{5}{2}^-)}(4520 \pm 150)$ is a good candidate to be a state which was observed in [1]: $5/2^?(4450 \pm 4)$ with a width of $\Gamma = 39 \pm 24$ MeV. Then the broad state, $3/2^?(3380 \pm 38)$ with $\Gamma = 205 \pm 94$ MeV also observed in the pJ/ψ spectrum, is a positive parity state, $3/2^+$.

An opposite classification of states is suggested in [23]: $3/2^?(3380 \pm 38) \rightarrow 3/2^-(S\text{-wave pentaquark})$ and $5/2^?(4450 \pm 4) \rightarrow 5/2^+(P\text{-wave pentaquark})$.

We suppose that the broad bump in the $3/2^+$ -wave is the result of rescatterings in pJ/ψ -channel, for example, such as $\Lambda_b \rightarrow \Lambda(1520)J/\psi \rightarrow K^-(pJ/\psi)$.

In the suggested scheme the mass interval (4040 – 4500) MeV should contain additionally several resonances with $J^P = 1/2^-, 3/2^-$. Some of them may dominantly decay into $p\eta_c$ -channel, concerning mainly the $1/2^-$ states.

The masses of pentaquarks with strange diquarks (cs), see eq.(9), are estimated quite similar to the non-strange ones.

In conclusion, the scheme of the low-lying pentaquark is suggested on the basis of the study of the tetraquark states [2]. We are convinced that the crossing studies of exotic mesons and baryons give a correct way for investigation of these topics.

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